# PHYSICS @ INO

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*NuFact 2013, August 19-24,*

*Beijing, China*

# The Unknowns...after $\theta_{13}$

- The neutrino mass ordering (MH)...
- CP violation in the lepton sector...
- Octant of the mixing angle $\theta_{23}$ ...
- Beyond 3-flavor oscillation physics..

# The Unknowns…after $\theta_{13}$

We will cover in this talk

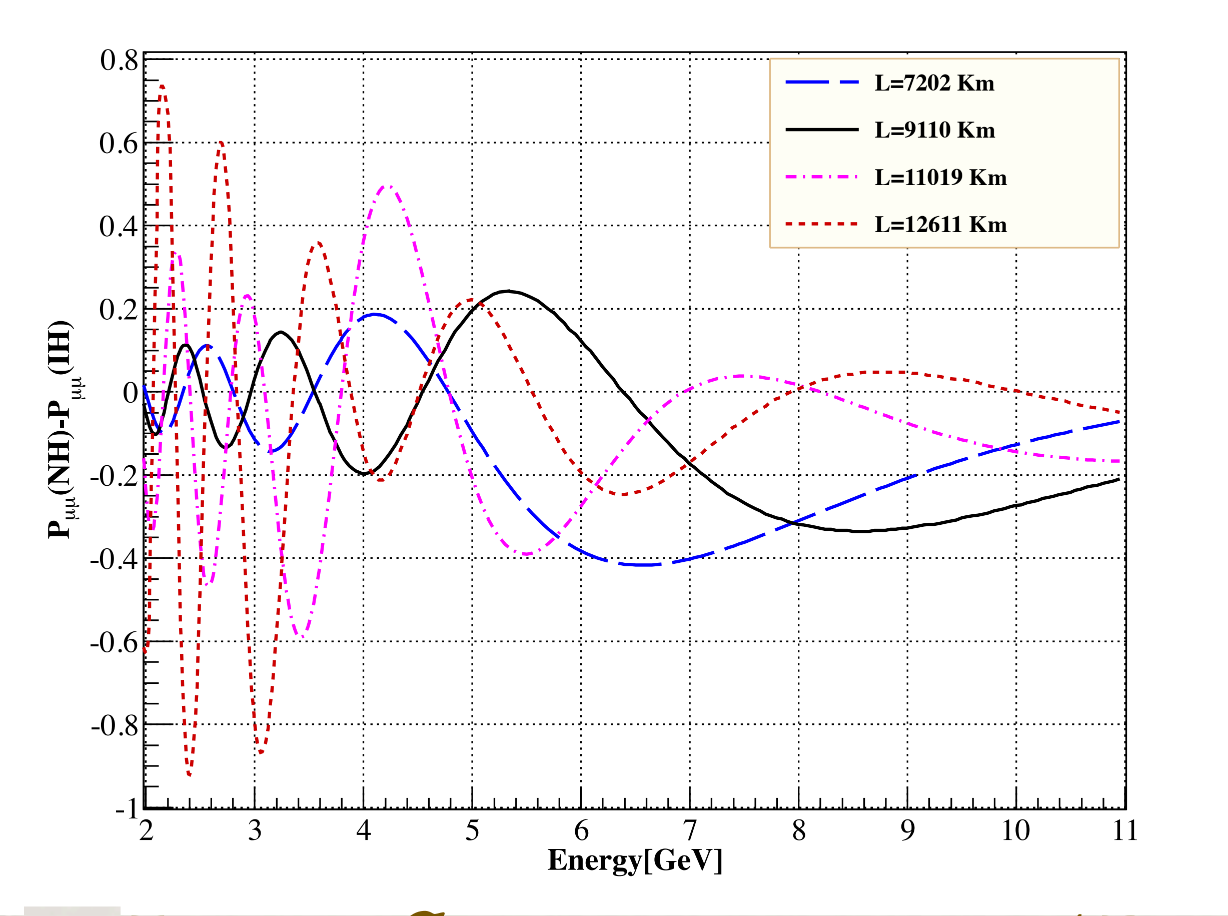
- The neutrino mass ordering (MH)…
- CP violation in the lepton sector…
- Octant of the mixing angle $\theta_{23}$ …
- Beyond 3-flavor oscillation physics…

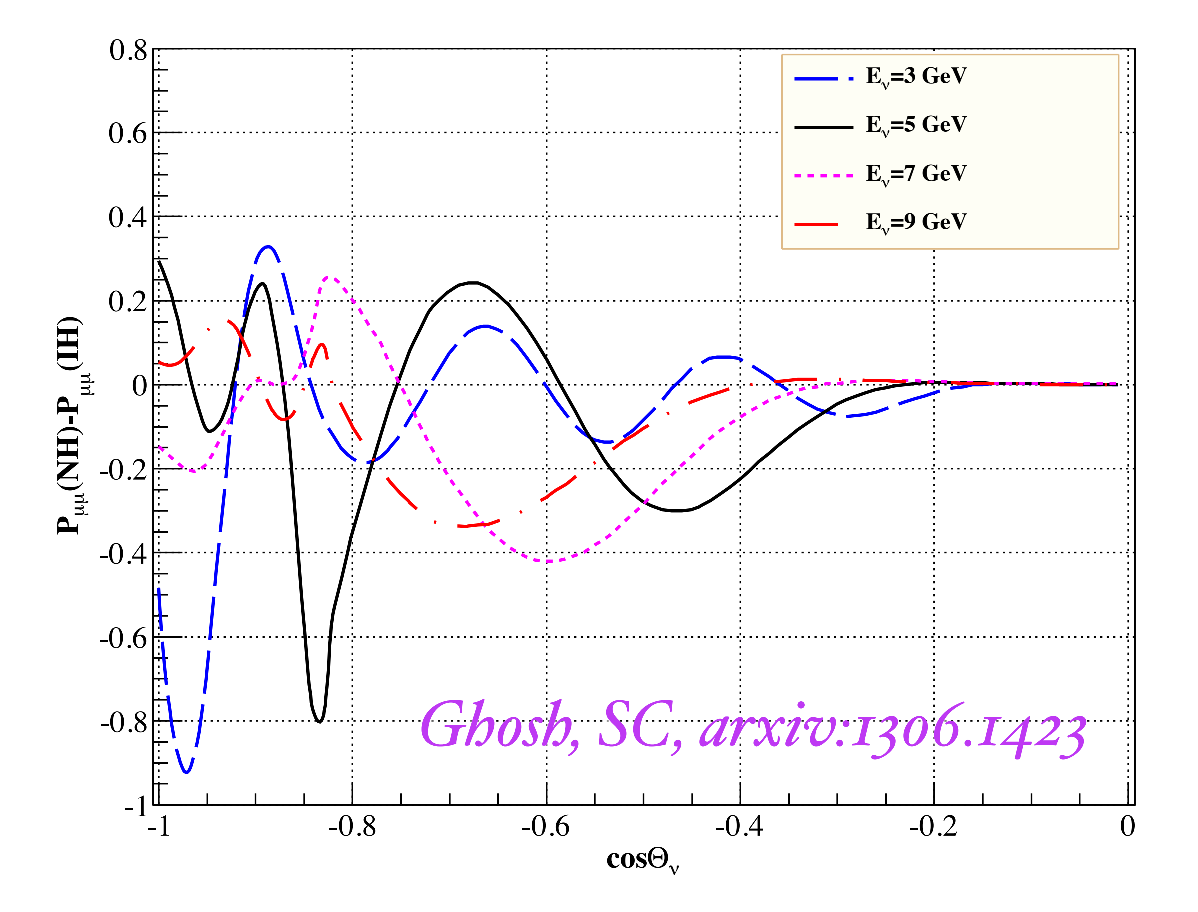
using atmospheric neutrinos

3 posters and a talk on details of INO
by Kaur, Laksmi, Meghna

Plenary talk by Naba Mondal on Friday

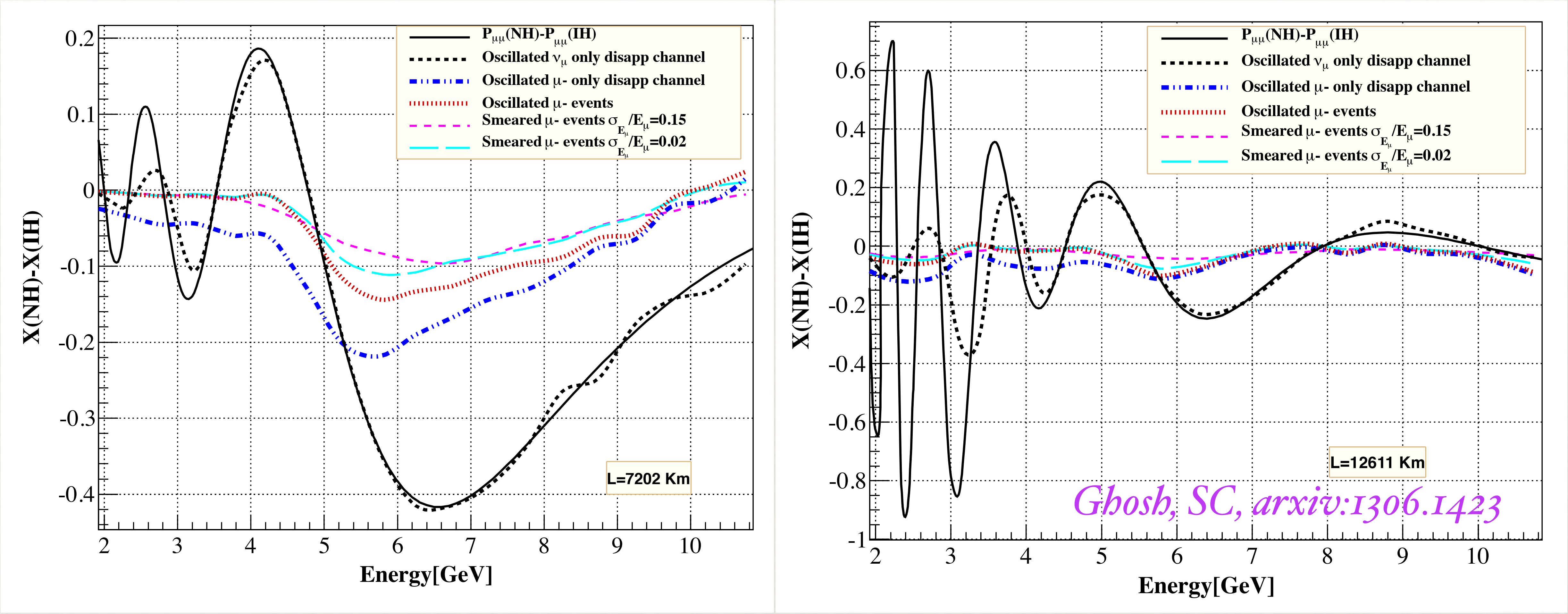
# Matter Effects in Neutrinos



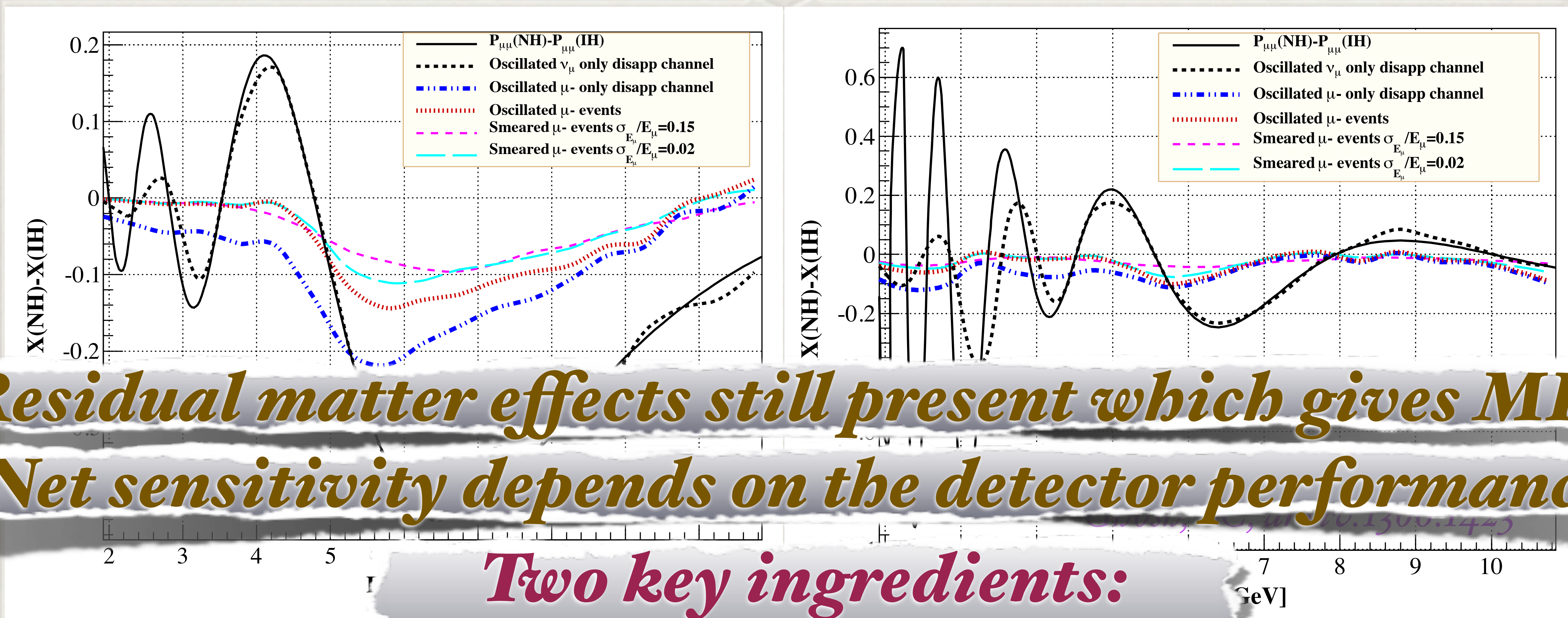

- Large fluctuations in $\Delta P$ in both E as well as $\Theta$
- Need good reconstruction in both E as well as $\Theta$ - resolution
- $\Delta P$ opposite for neutrino and antineutrino - charge id

# Matter Effects in Muons




- *Smearing due to the ν-nucleon cross-section*
- *Smearing due to presence of both $\nu_\mu$ and $\nu_e$ in the atm flux*
- *Smearing due to finite detector resolution*

# Matter Effects in Muons



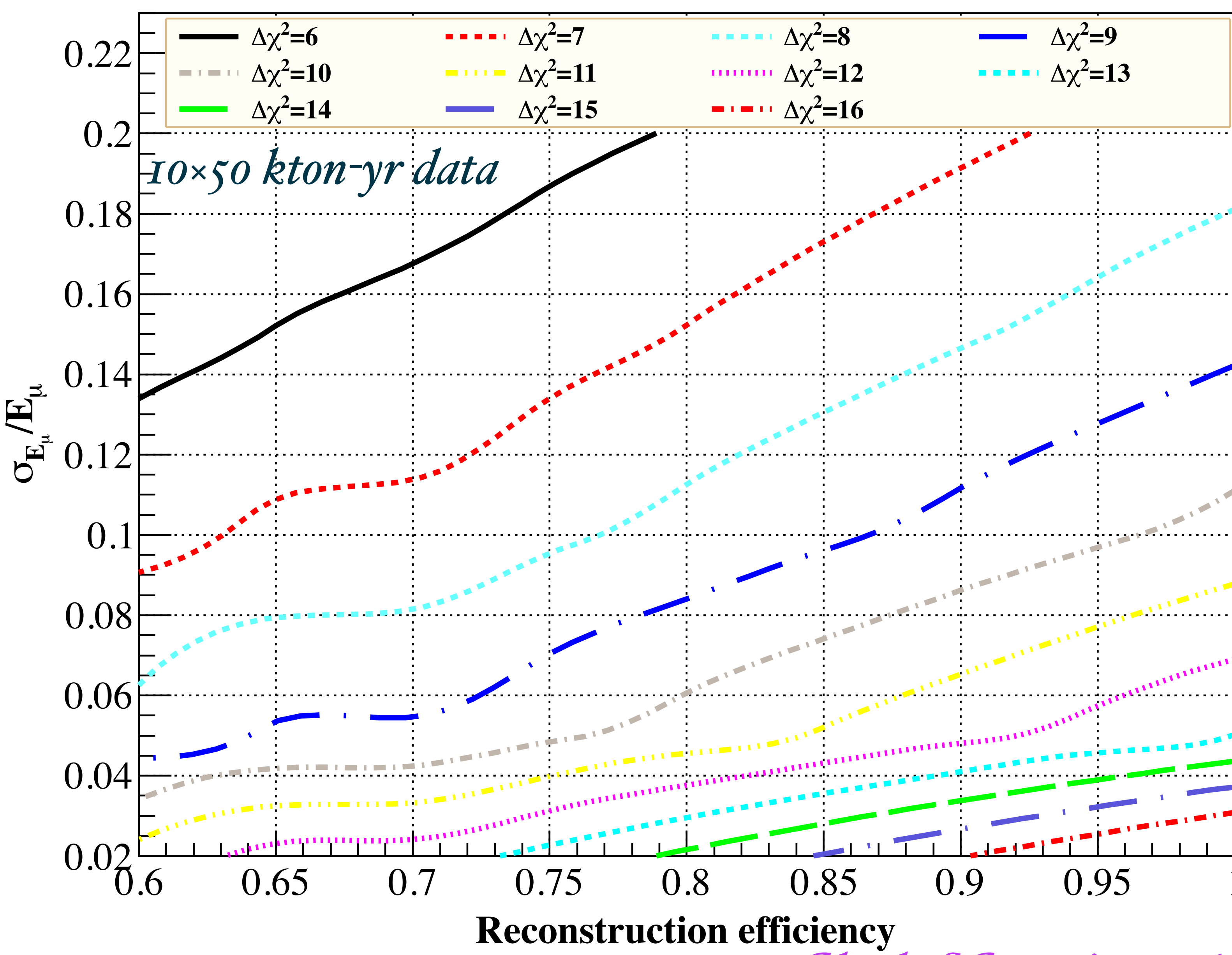

**Residual matter effects still present which gives MH**

**Net sensitivity depends on the detector performance**

**Two key ingredients: Resolution and Efficiency**

- *Smearing d*
- *Smearing due to presence of both $\nu_\mu$ and $\nu_e$ in the atm flux*
- *Smearing due to finite detector resolution*

# MH @ INO (Only Muons)




*Ghosh, SC, arxiv:1306.1423*

*INO μ angle resoln is good*

*We take $\sigma_{\cos\Theta}$=0.025*

*For $\sigma_E/E$<4% and ε>95%*

*$\Delta\chi^2$>14 (muons)*

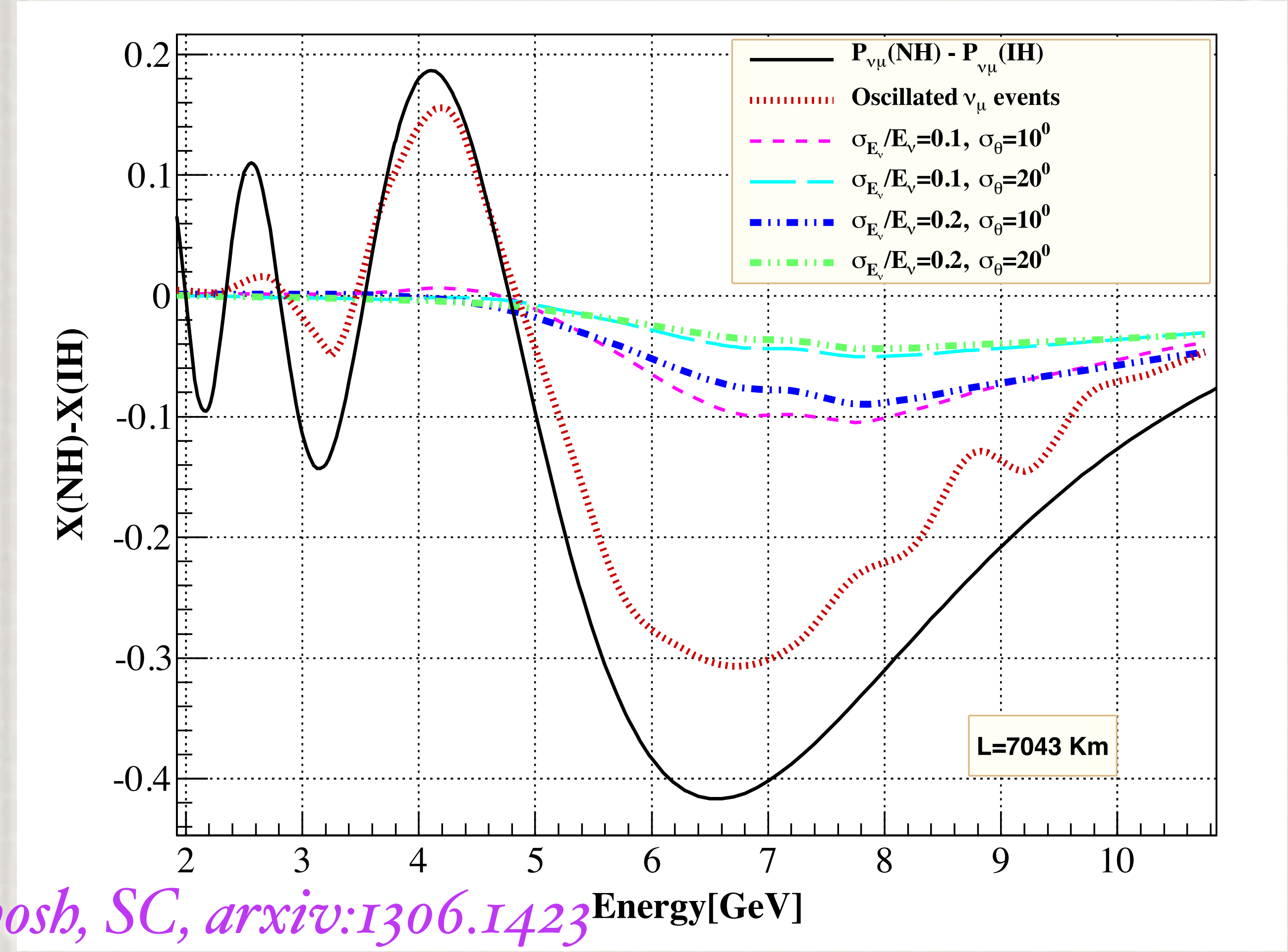
*For $\sigma_E/E$<5% and ε>90%*

*$\Delta\chi^2$>12 (muons)*

*For $\sigma_E/E$<11% and ε>80%*

*$\Delta\chi^2$>8 (muons)*

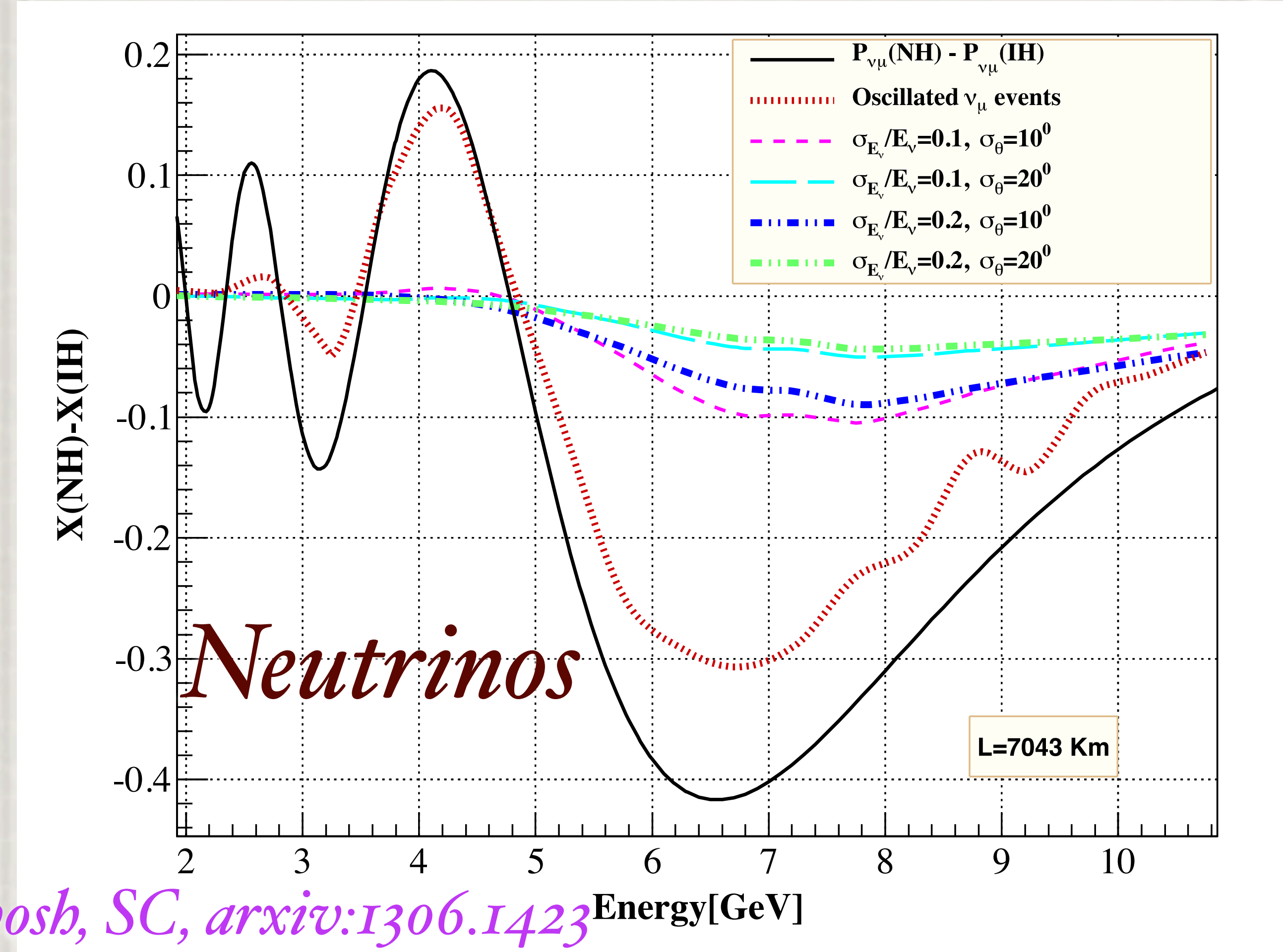
# Matter Effects in Neutrinos



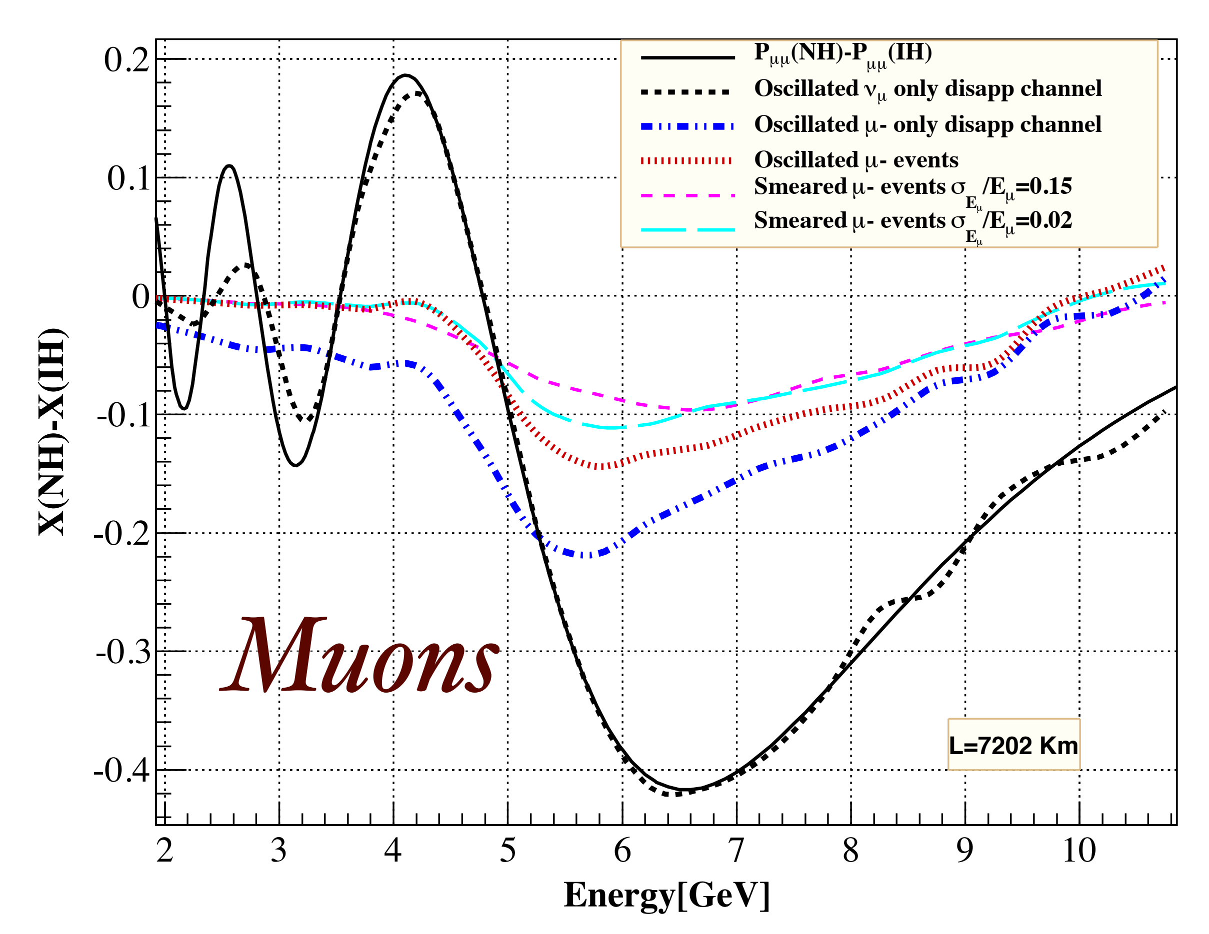

*Ghosh, SC, arxiv:1306.1423*

- *Detector resolutions *extremely crucial**

# Matter Effects in Neutrinos

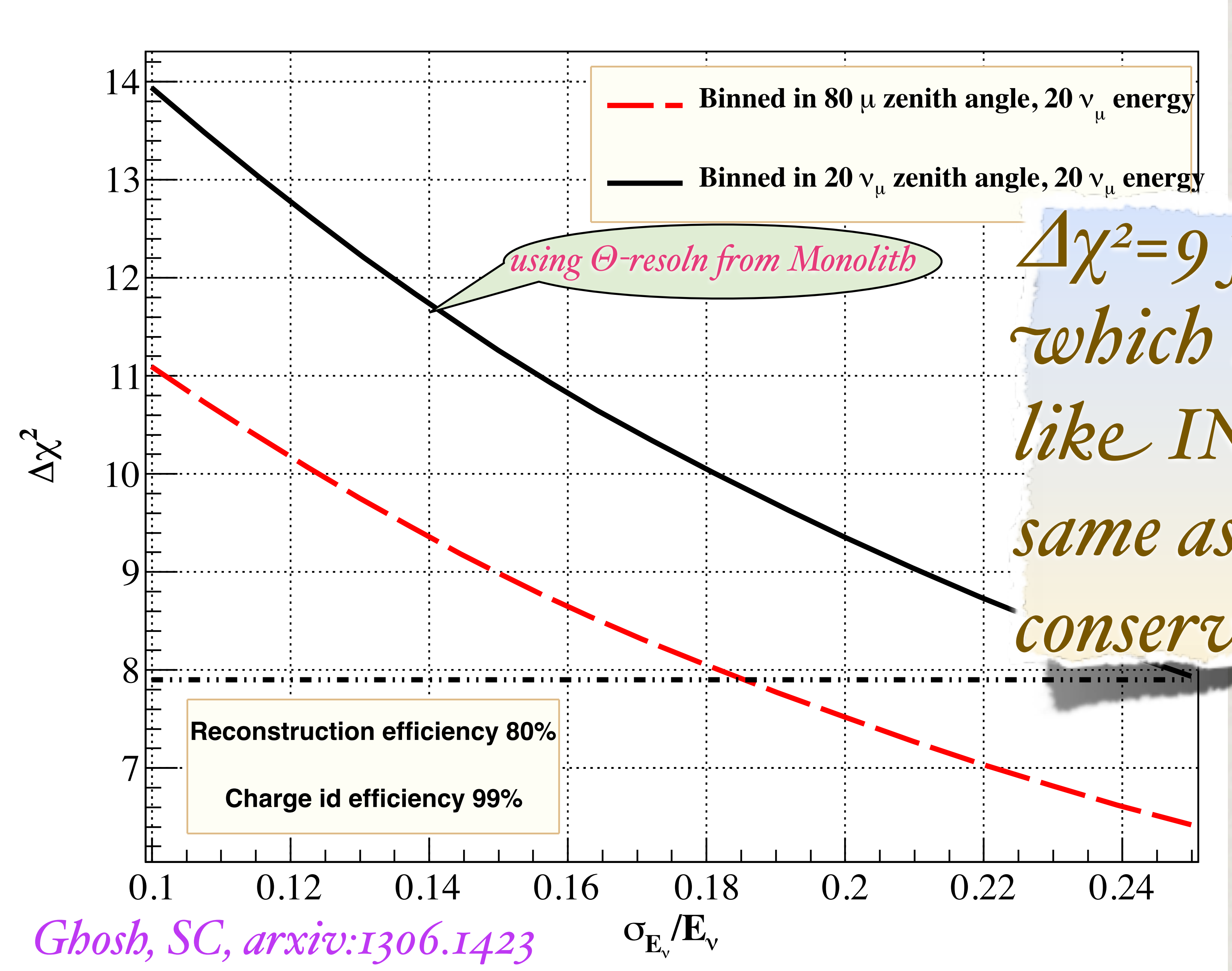



Ghosh, SC, arxiv:1306.1423




- *Net matter effects in neutrinos and muons is the same after putting detector resolutions - even for very optimistic neutrino resolutions*

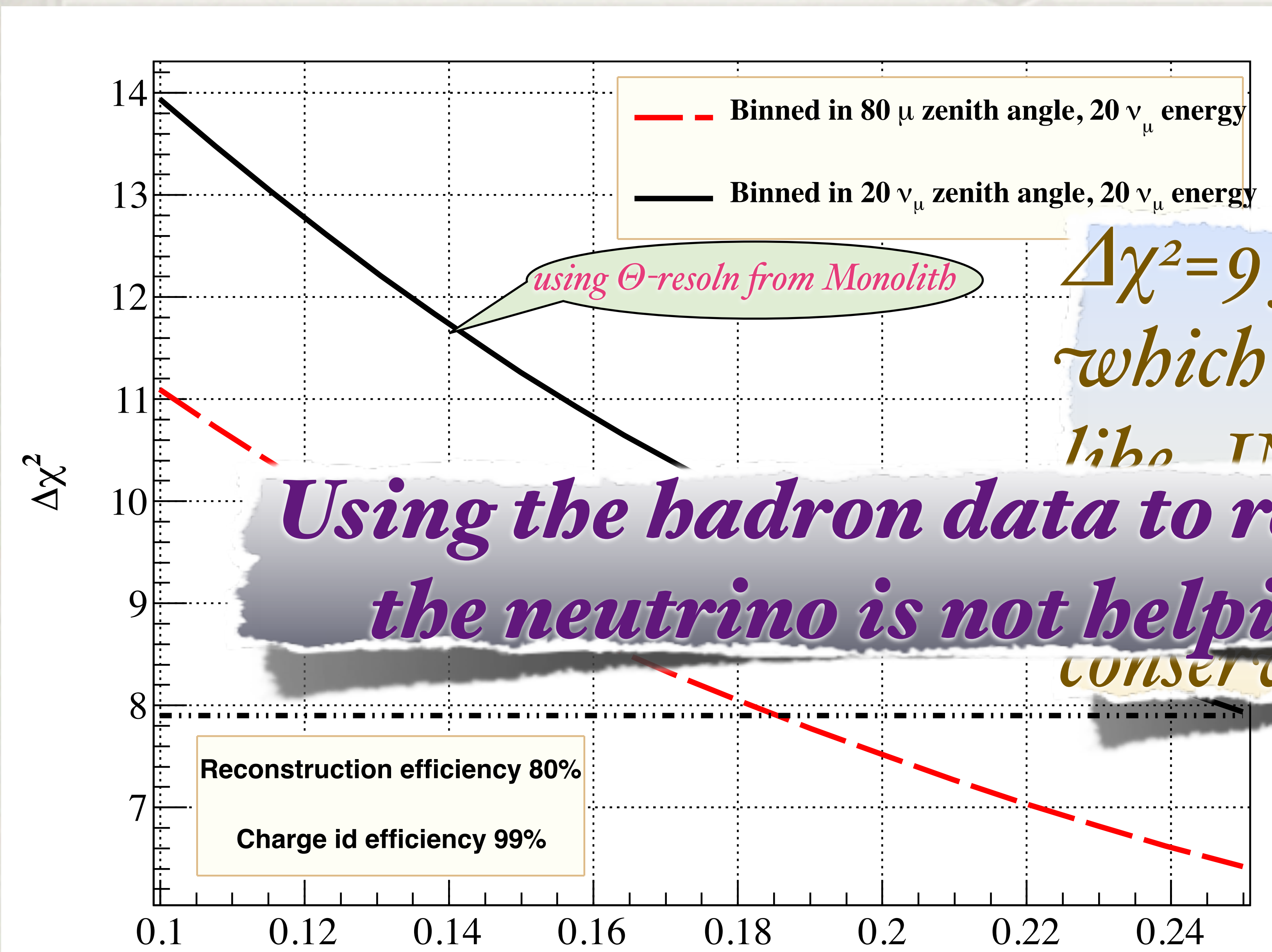
# Matter Effects in Neutrinos




*Ghosh, SC, arxiv:1306.1423*

*$\Delta\chi^2$=9 for 21% E-resoln which is the E-resoln for dets like INO/MIND- this is the same as you get from a *very* conservative muon analysis!!*

# Matter Effects in Neutrinos



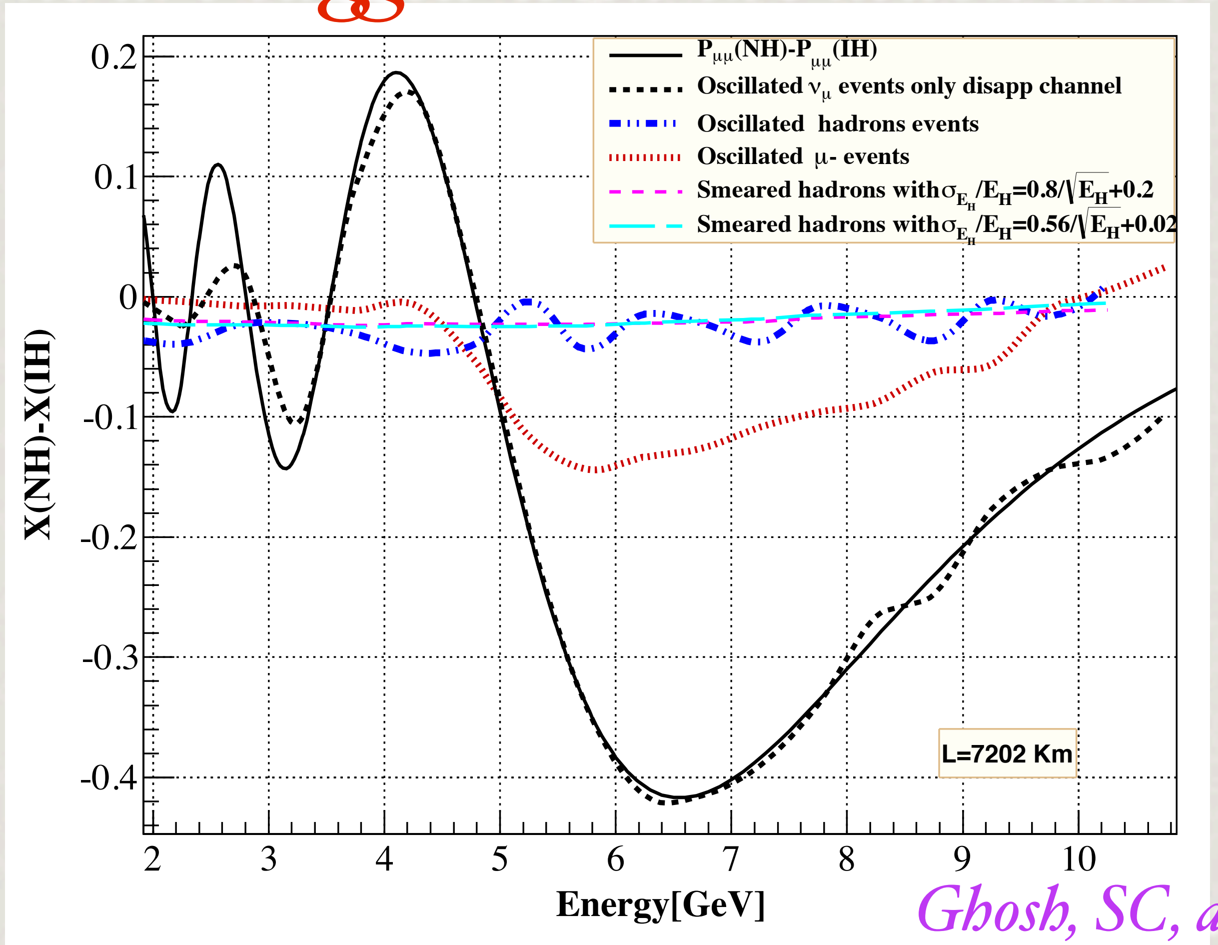

*Ghosh, SC, arxiv:1306.1423*

*$\Delta\chi^2=9$ for 21% E-resoln which is the E-resoln for dets like INO/MIND- this is the ... *very* conservative muon analysis!!*

***Using the hadron data to reconstruct the neutrino is not helping much***

# Matter Effects in Hadrons

*Hadrons are tagged with the muon direction*

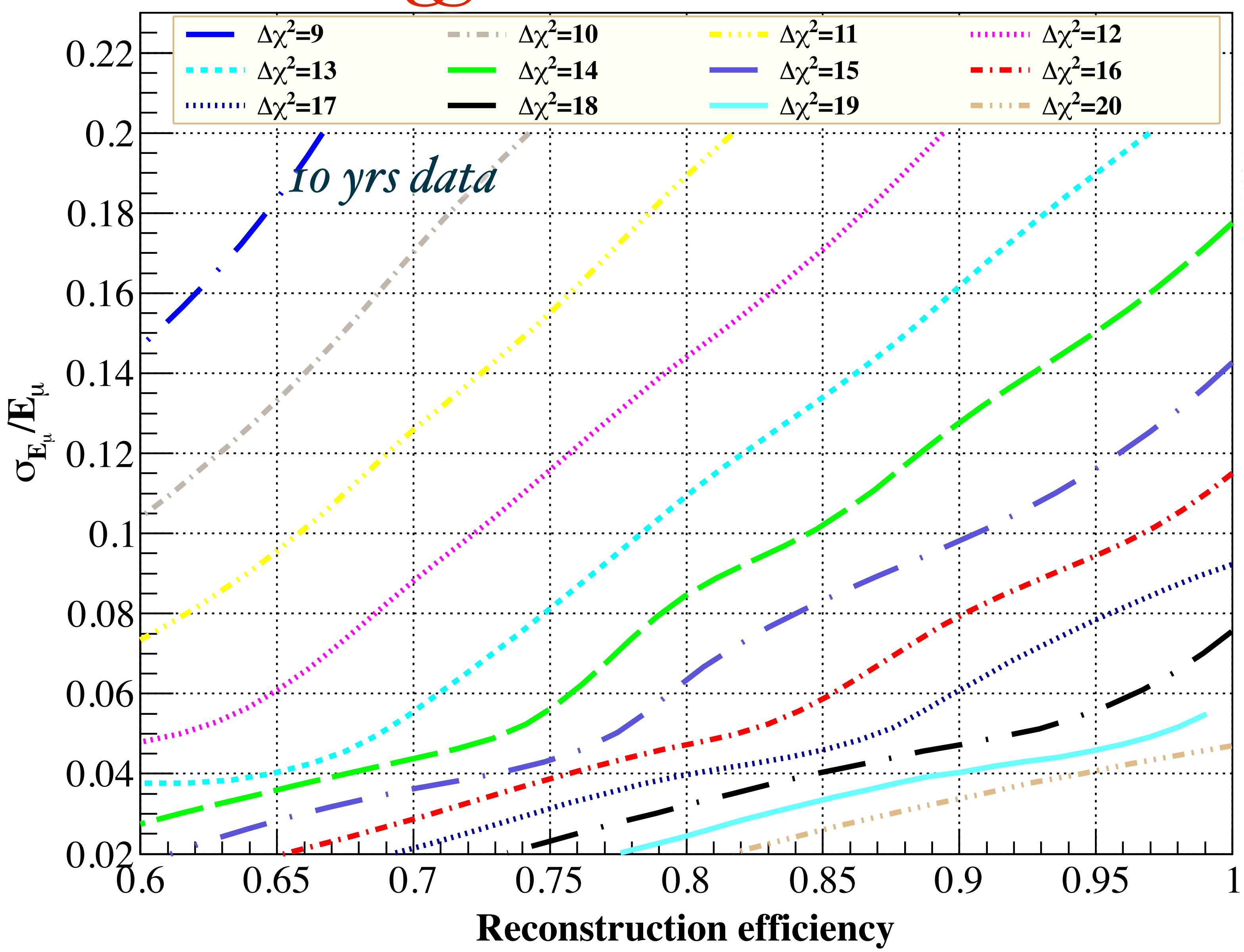



*Ghosh, SC, arxiv:1306.1423*

- *Matter effects in hadrons present...will give MH sensitivity*
- *Though significantly less than in muons*
- *Detector resolution less important for hadrons*

# MH@INO(Muon+Hadron)

*Hadrons are tagged with the muon direction*




*Ghosh, SC, arxiv:1306.142*

For $\sigma_E/E<4\%$ and $\varepsilon>95\%$

$\Delta\chi^2>20$ (muons+hadrons)

$\Delta\chi^2>14$ (muons)

For $\sigma_E/E<5\%$ and $\varepsilon>90\%$

$\Delta\chi^2>18$ (muons+hadrons)

$\Delta\chi^2>12$ (muons)

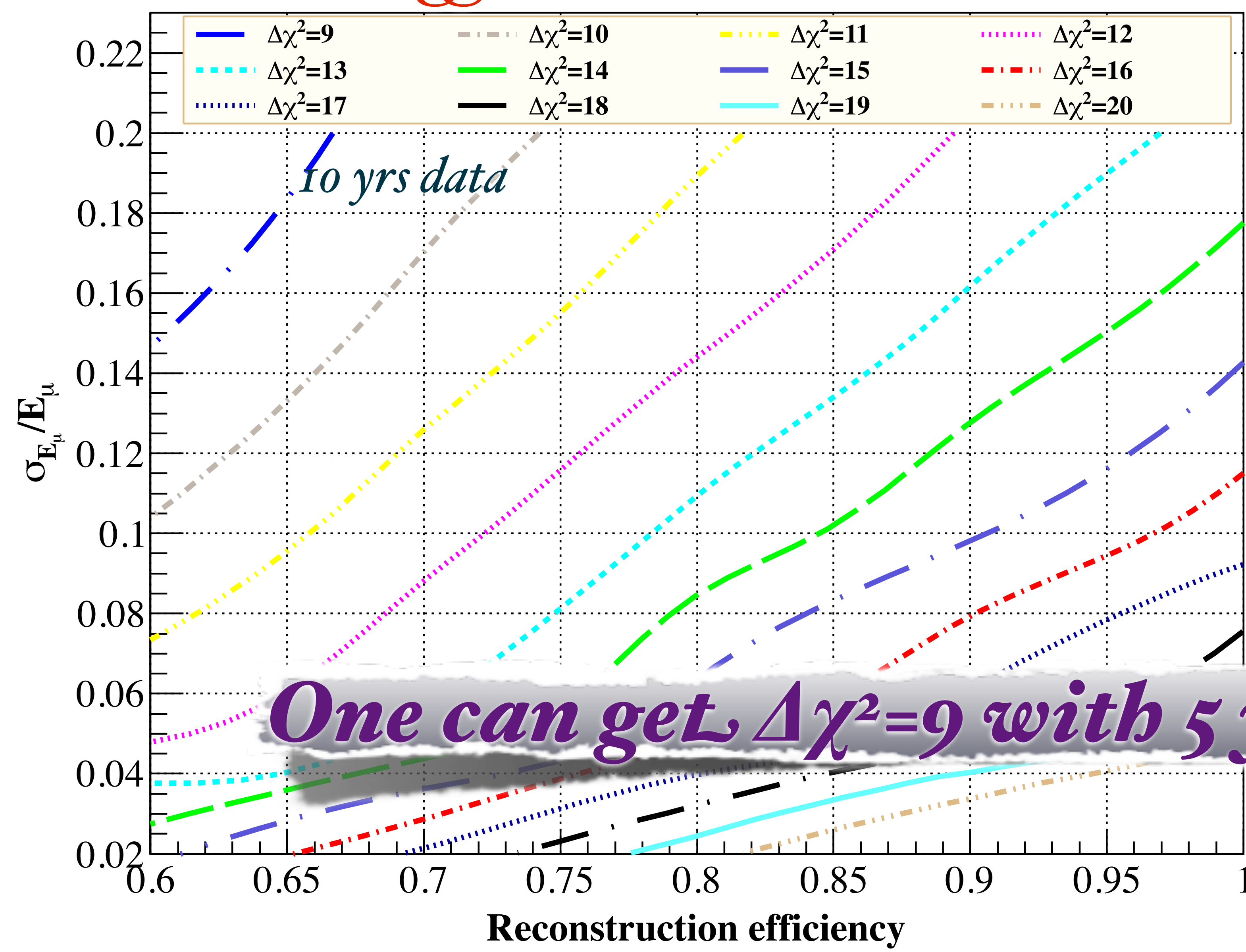
For $\sigma_E/E<6\%$ and $\varepsilon>85\%$

$\Delta\chi^2>16$ (muons+hadrons)

$\Delta\chi^2>10$ (muons)

# MH@INO(Muon+Hadron)

*Hadrons are tagged with the muon direction*

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For $\sigma_E/E<4\%$ and $\varepsilon>95\%$
$\Delta\chi^2>20$ (muons+hadrons)
$\Delta\chi^2>14$ (muons)

For $\sigma_E/E<5\%$ and $\varepsilon>90\%$
$\Delta\chi^2>18$ (muons+hadrons)
$\Delta\chi^2>12$ (muons)

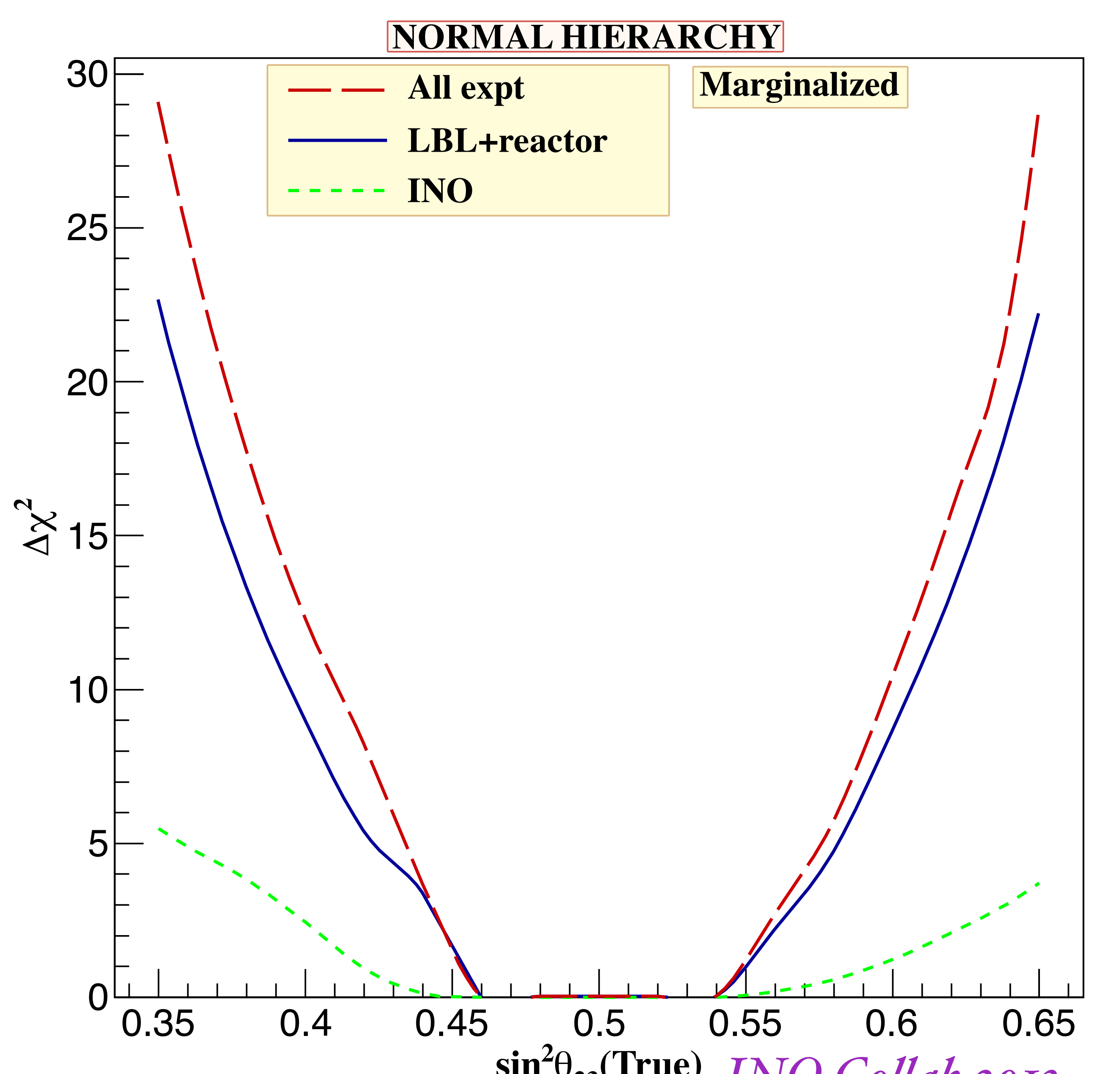
**One can get $\Delta\chi^2=9$ with 5 years INO data**

For $\sigma_E/E<6\%$ and $\varepsilon>85\%$
$\Delta\chi^2>16$ (muons+hadrons)
$\Delta\chi^2>10$ (muons)

# MH - $\mu$+h vs $\nu$ Analysis

- Muon+Hadron analysis gives $\Delta\chi^2=16$ for $\sigma_E(\mu)=6\%E$ and $\sigma_\Theta(\mu)=0.025$ in $\cos\Theta$ .... both are realistic for INO/MIND
- To get the same $\Delta\chi^2=16$ using the neutrino analysis, one needs $\sigma_E(\nu)=10\%E$ and $\sigma_\Theta(\nu)=7.3^o$....the energy resol requirement not possible at INO/MIND
- Better to use the hadron data separately in the $\chi^2$ than using it to reconstruct the neutrino energy and angle

# Octant @ INO




*INO Collab 2013*

For $\sin^2\theta_{23}<0.4$

$\Delta\chi^2>2.44$ (INO)

$\Delta\chi^2>9$ (LBL+React)

$\Delta\chi^2>12.3$ (INO+LBL+React)

Sensitivity for IH is worse

# Conclusions

- With 5% $E_\mu$-resoln and 90% efficiency, INO will have $\Delta\chi^2=12$ in 10 years from muon data alone
- If we tag the hadrons with the muons and add the hadron data separately into a combined analysis, then with 5% $E_\mu$-resoln and 90% reconstruction efficiency INO could have $\Delta\chi^2=9$ in just 5 years
- Using the hadrons to reconstruct the neutrino energy and directions will always yield poorer results